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Microsystems, Complexity, and the Adaptive Battlefield

"No battle-plan ever survives contact with the enemy!"

These words of 19th century Prussian Field Marshal Helmuth von Moltke seem more true today than ever. Today, we call that agile and adaptive behavior. The other guys adapt; we adapt. And sometimes the plans go out the window.

The complexity and rapid change of modern society and modern conflict challenge our ability to stay ahead of the power curve. Adversaries, such as the insurgents in Iraq and Afghanistan, are challenging us using the very technology, mobility, and miniaturized systems that our technological advances have provided: cell phones for military communications and garage door openers to detonate improvised explosive devices (IEDs). They're using the Internet to share intelligence, to recruit more insurgents, and to rally support and influence politics.

We've introduced technology to benefit the civilian world and now find our adversaries adapting that technology for military use against us. This calls to mind a more contemporary scholar, Murphy, whose famous laws tell us that if something can go wrong, it will.

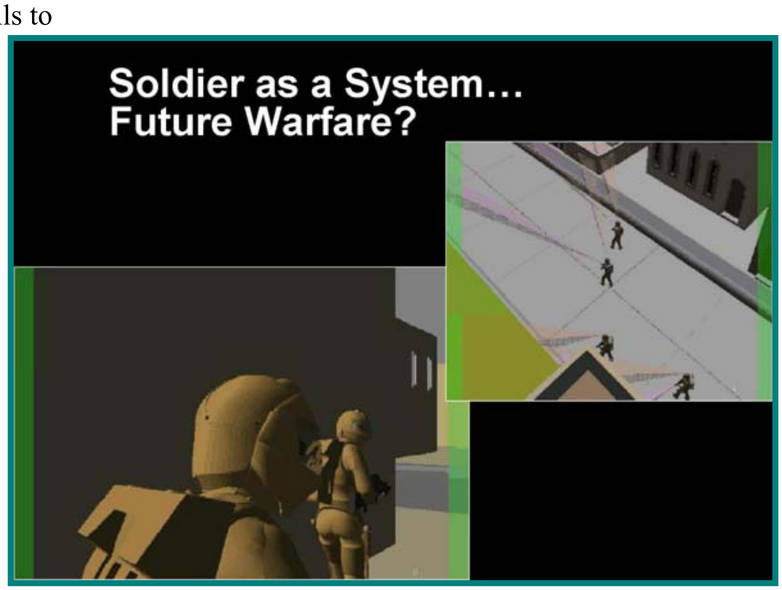
Perhaps Marine Corps General Charles Krulak had Murphy in mind when he developed the concept of the "Strategic Corporal," an adaptable leader operating at the lowest levels of our infantry services with the intelligence and independence to take whatever action was most appropriate for the situation, from handing out food rations to refugees, to dealing with an insurgent gang hiding around the corner.

Taking a cue from the Strategic Corporal, we need to be opportunistic and adaptable in our use of technology. Perhaps we need to think like "technological insurgents," looking for new ways to adapt existing hardware to rapidly create and field systems with greater effectiveness and at lower cost.

Let me give you an example. Last year at DARPATech, Brad Tousley from TTO told us about distributing sensor platforms among the individual warfighters, so any Soldier, any Marine, could be an advanced sensor platform.

The goal would be to find our adversary in three dimensions, behind his walls, to "see" his communications. Sensing and signal processing would be distributed and flexible. We could track snipers' bullets and rocket-propelled grenades (RPGs) and aid with automated weapons targeting, even in the complex urban battlespace.

One challenge that comes with this great idea is the enormous computational burden required for signal



processing algorithms to cut through the heavy urban clutter and expose our adversaries. We'd need real-time adaptive beam forming and imaging algorithms. Using today's digital signal processing and reduced instruction set chip (DSP/RISC) architectures, this would require many, many chips and kilowatts of power, a virtual supercomputer on the back of every dismount. Is there another way?

Today's video game systems—Play Station II, X-Box, Game Boy—all can do image rendering with gigaflop processing. Those games start with an abstract model of the world and generate what we would sense if we were there, realistically rendering stunning graphics in real time. With mathematics, we can run that problem backwards: given actual sensed data, and understanding the physics and geometry, we can figure out things we'd like to know about the actual world that generated the sensed data. For instance, one sophisticated algorithm that helps us find real-world targets from radar measurements in heavy clutter is Space Time Adaptive Processing (STAP).

We are demonstrating the hardware used in your child's handheld Game Boy can perform complex real-time computations like STAP: our "STAP-Boy" effort is looking to pack the equivalent of 100 standard signal processors into a low-power handheld supercomputer using a few commercial graphics processors.

What's more, these COTS chips use software based on open standards for graphics that a whole generation of really smart kids are learning in high school! Could it be that our grade school children understand new technology better than we do?

Using commercial gaming technology and programming by some high school kids, we should be able to develop advanced, adaptable, militarily useful computational capabilities to process RF data collected from distributed, dismount-carried sensors and emitters.

As for those emitters, military radar systems can weigh thousands of pounds and cost hundreds of thousands of dollars.

Modern WiFi systems use tiny hardware and cost tens of dollars. Modifications to simple WiFi technology can provide a transceiver that can operate from a few KHz to 10 GHz and fit into the size of a memory stick. Coupled to the STAP-Boy handheld through its USB port, we could use this for everything from communications through SIGINT. These units would communicate with each other in an auto-adaptive network. We could see through the walls or take control of enemy cell phones. We could use the enemy's transmitters against them as part of our sensor network. We could provide targeting and guidance for cheap munitions.

Let's start thinking beyond adapting existing technologies for new purposes. Let's start thinking about technologies that adapt themselves to the situation. Inspired by General Krulak's Strategic Corporals adapting on the fly to make their whole unit more agile and effective from the bottom up, we need components that act as "strategic microsystems," components that can adapt to build larger, self-optimizing, self-repairing, self-networking systems. With these, we can create auto-adaptive systems that could recover and perform in the most adverse of environments. They would work, even if just a little, no matter what we throw at them.

Auto-adaptive systems would be built with Murphy's Laws in mind. Things will go wrong, and we should expect them to, so let's develop auto-adaptive systems that adapt robustly to whatever Murphy throws at them. For example:

- Murphy's Military Law 36: Your equipment was made (and integrated) by the lowest bidder.
- Murphy's Military Law 50: Radios function perfectly until you need fire support.

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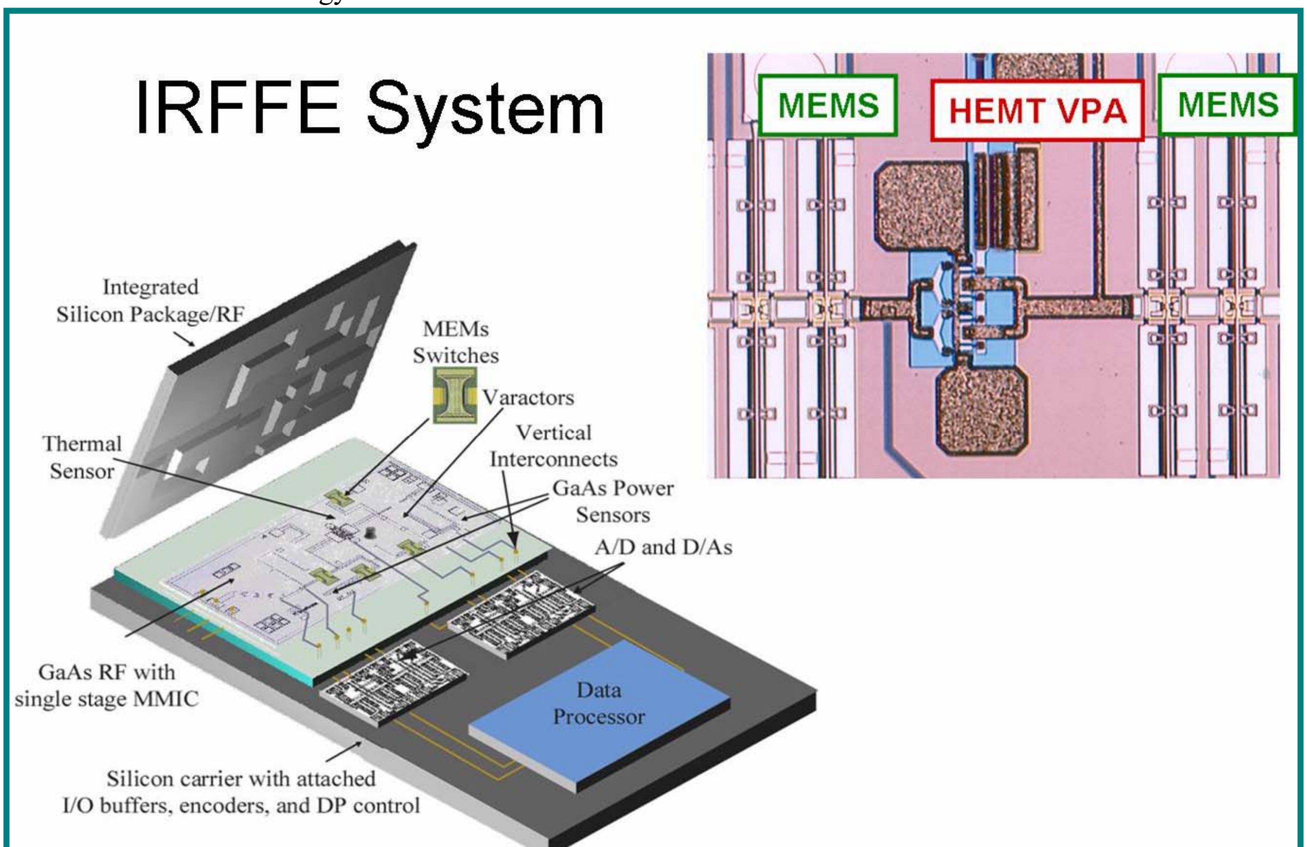
Communications, radars, and electronic warfare systems tend to have application-specific RF front ends that are carefully tuned by hand to produce optimum performance over a fairly narrow operating condition. Change the application and we build a different system with different components. And, of course, vibration, temperature variation, and aging all eat away at performance.

DARPA's Intelligent Radio Frequency Front Ends (IRFFE) program aims to change this by creating early examples of strategic microsystems: in this case, smart RF components enabling auto-adaptive, reconfigurable RF systems that sense their internal and external environments and automatically match impedances and biases through the subsystem, enabling unprecedented agility for diverse DoD radar and communication system applications. It also offers significant cost savings over the entire system life cycle by simplifying system design, reducing maintenance and inventory, and extending the operational lifetime. IRFFE technology will increase manufacturing yields by giving components the capacity for self-compensation, providing high performance despite fabrication variations.

Self-compensation, automated reconfigurability, and exploiting commercial technology are new ways to cut a path to high-performance auto-adaptive systems from cheap components. Dramatic advances in nonlinear signal processing can also help get excellent RF system performance from less than stellar components RF components.

Specifically, we want RF systems providing the highest possible linear dynamic range in order to see small target signals in a thicket of strong electromagnetic interference and clutter. However, when we add emerging requirements for large instantaneous bandwidths, affordable RF front ends exhibit significant nonlinear behavior that tends to scramble the strong interference with the weak targets, making it very hard to find the bad guy.

Familiar linear signal processing algorithms, such as those based on the FFT, can help tease apart signals from interference, if those algorithms are



fed by RF front ends providing highly linear performance across the bandwidth. However, in the real world, that's often not the case, and linear signal processing can't unravel the really difficult parts of nonlinearly scrambled signals and interference.

Novel digital signal processing algorithms and hardware offers a potential solution we call nonlinear equalization (NLEQ), a technique capable of untangling most of this scrambling. DARPA is developing NLEQ as a simple hardware application for existing RF systems, which trains itself to provide the inverse response of any particular system it is applied to, canceling its particular nonlinear distortions across the frequency bandwidth.

We're showing that a COTS digital receiver with a trained NLEQ nearly eliminates the effects of component-generated nonlinearities without distorting the signals of interest. This allows us to see, exploit, and prosecute previously obscured signals of interest with today's hardware, instead of waiting for sufficiently improved components.

The lesson is that smart and adaptive digital signal processing, which will soon run on commodity digital hardware, can be used to circumvent years of component engineering and development.

Murphy's Law 10: The quartermaster has only two sizes: too large and too small.

There's a problem with cameras and optics. If they have good resolution, they're too big; if they're small, the image isn't very good. We have flat panel displays; why no flat cameras?

Mathematical dimensionality reduction gives us a new game, trading optics and digital processing. Using "compressive sensing," we can make a large aperture camera with a high resolution that is flat as a pancake! Instead of making everything else fit the camera, imagine cameras that fit the application, like a UAV wing or a soldier's helmet.

The beauty of compression is that we keep only the important information, which is a tiny fraction of the data available. This is what makes it possible for us to watch 2-hour movies on DVDs and to send videos over the internet despite the bandwidth limitations. In the same way, compressive sensing lets us measure only the important information, so we don't need enormous measurement bandwidth. This is the trick we are using to compress the analog optics of a camera. This idea may be applicable to RF signals as well, potentially transforming analog-to-digital conversion into analog-to-information conversion.

These are a few examples of advanced mathematics enabling explorations of novel design spaces, directing self-adapting components and systems, and enabling opportunistic exploitation of technology advances in the commercial marketplace. These are a few early steps on a path I hope leads well beyond straightforward extensions of today's technology that can be quickly countered by adversaries and creatively used against us. Which brings us to:

Murphy's Military Law 54. When in doubt, empty the magazine.

Some might say I want the impossible: Adaptable systems, low cost, high function, and all available by close of business yesterday. Systems that survive contact with the enemy and with the real world. I want systems organized from the bottom up so they can't go wrong or, if they do, they fix themselves.

A new vision is needed if we are to anticipate and adapt to the chaos dished up by adversaries in our future. Let's look for a new systematic approach to rapidly design and integrate strategic microsystems into agile and robust auto-adaptive systems. I am certain this community is up to the challenge.